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RESEARCH MEMORANDUM

EFFECT OF INTERSTAGE BLEED ON ROTATING STALL AND BLADE VIBRATION IN A 13-STAGE AXIAL-FLOW COMPRESSOR IN A TURBOJET ENGINE

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SUMMARY

A rotating-stall and blade-vibration survey was conducted on a modified production turbojet engine incorporating a 13-stage axial-flow compressor with a design pressure ratio of approximately 7 and a sea-level airflow of 120 pounds per second. The engine was modified to install interstage air-bleed systems over the fifth and tenth rotor stages. Hot-wire anemometors and resistance-wire strain gages were used to measure the effect of fifth- and tenth-stage bleed-flow rate on rotating stall and rotor-blade vibration.

The maximum vibratory stresses without bleed occurred at 60 and 68 percent of rated speed in the first and second stages, respectively. These vibrations were excited by the second harmonic of the three-zone relative stall frequency. Either the fifth- or tenth-stage bleeds changed the three-zone stall pattern to a four- or five-zone pattern which was not in resonance with the natural bending frequency of the blades, and thereby eliminated the high vibratory stresses. The fifth-stage bleed required a lower flow rate to eliminate the rotating-stall-excited rotor-blade vibrations than the tenth-stage bleed.

INTRODUCTION

In recent years, the pressure ratio of axial-flow compressors has been increased appreciably in order to improve engine fuel economy and thrust. These multistage compressors have inherent characteristics of choking at the exit stages, and as a result stalling in the inlet stages at speeds below design speed. The inlet stages do not stall uniformly, but instead stall in zones that rotate in the same direction as the compressor rotor at about one-half compressor speed. This phenomenon has been termed "rotating stall." Rotating stall excites serious compressor blade vibrations (refs. 1 and 2), and, therefore, its control or elimination is extremely important. The NACA Lewis laboratory has conducted a series of research programs on production jet engines to determine the

effect of variable geometry and inlet conditions on rotating stall. These programs were conducted to determine the effect on rotating stall of inlet baffles (ref. 3), inlet-air temperature (ref. 4), and variable inlet guide vanes (refs. 5 and 6).

A fundamental solution to the problem of the rotating stall would be to increase the airflow rate in the inlet stages and thereby increase the axial velocity and thus decrease the angle of attack. This could be accomplished by bleeding air from the intermediate stages and permitting the inlet stages to pump the increased airflow regardless of the exit-stage choking condition. The results of an investigation in which a 13-stage axial-flow compressor was equipped with interstage bleed over the fifth and tenth rotor stages and operated as part of a turbojet engine are reported herein.

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This investigation was conducted at the Lewis laboratory in a sea-level static test stand. The vibratory stresses were determined by the use of resistance-wire strain gages, and flow fluctuations of rotating stall were detected by constant-temperature hot-wire anemometers mounted in radial survey devices. The engine was equipped and operated with a variable-area exhaust nozzle in order to obtain some variation in pressure ratio at any selected speed.

APPARATUS AND INSTRUMENTATION

Turbojet engine and installation. - The investigation was conducted on a turbojet engine incorporating a 13-stage axial-flow compressor with a design pressure ratio of approximately 7, a rated engine speed of 8300 rpm, and a sea-level airflow of approximately 120 pounds per second. The engine, which was operated in a sea-level test stand, was equipped with an adjustable exhaust nozzle to permit variations in pressure ratio and airflow at a given constant speed. When the variable exhaust nozzle was in the full-open position, the nozzle area was equivalent to the normal rated area for this engine.

The compressor cases were modified for installation of an interstage bleed system over both the fifth and tenth rotor stages. Figure 1 shows the machined bleed passages through the compressor case. Figure 2 shows the cross section of the fifth- and tenth-stage bleed passages, and the length and circumferential position of each slot. The width of the slots was approximately equal to the projected chord length of the rotor blades in the respective stages. The exact position of the bleed slots was dictated by the location of engine accessories. The external piping associated with the bleed system is shown in figure 3. The air was bled through these slots into the collector rings and through a piping system containing flow-measuring orifices and remotely controlled valves and then discharged through the exhaust muffler to the atmosphere. The fifth and tenth stages each had independent bleed systems.

Hot-wire anemometer. - A constant-temperature hot-wire anemometer system as described in reference 7 was used to detect the flow fluctuations of rotating stall. The anemometers were installed in radial-survey devices located in the first, second, and third stator passages.

Equipment for determining vibratory stresses. - Commercial resistance-wire strain gages, used to determine the rotor-blade vibratory stresses, were cemented to eight blades in each of the first three stages and four blades in the fourth stage. The eight blades per stage were arranged in two groups of four blades approximately 180° apart. In the fourth stage the four blades were together in one group. The gages were located at approximately midchord and close to the blade base. The lead wires were run from the strain gages to a 19-ring slip-ring assembly mounted on the front of the engine starter. The slip-ring assembly and strain-gage circuits were the same as reported in reference 8. A 12-channel oscillograph was used to record the strain-gage and hot-wire anemometer signals.

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PROCEDURE

The investigation was conducted in a sea-level static test stand with the compressor inlet and the turbine exhaust open to the atmosphere. The engine was operated with a variable-area exhaust nozzle. When the exhaust nozzle was in the full-open position, the engine operated with rated engine temperature ratio at equivalent rated speed. In order to simulate conditions encountered during engine acceleration, the engine was operated at reduced nozzle areas thus forcing the compressor to operate with higher pressure ratios.

The reduced nozzle area used in the tests was that area required to cause the engine to operate with an approximate increase of 250° F in tailpipe gas temperature.

As the engine was operated with the two exhaust-nozzle positions at different speeds, either the fifth- or tenth-stage bleeds were operated with various amounts of airflow. The hot-wire anemometer and strain-gage signals were observed and recorded during engine operation in order to determine the rotating-stall patterns and vibratory stresses present.

RESULTS AND DISCUSSION

Rotating Stall and Blade Vibration without Bleed

The correlation between rotor-blade vibrational frequencies and the relative frequencies of the three-zone rotating stall is presented in figure 4, which shows frequency plotted against percent of rated engine

speed. The data points represent the measured vibrational frequencies of the first and second rotor stages, and the solid line represents the second harmonic of the three-zone relative stall frequency. The relative stall frequency, or exciting frequency relative to the rotor blades, is defined as

$$f_s' = \frac{N\lambda}{60} - f_s$$

where

f_s' relative stall frequency, cps

N compressor speed, rpm

λ number of zones in stall pattern

f_s absolute frequency determined from hot-wire signals, cps

The three-zone stall pattern was the predominant rotating-stall pattern and was present when the blade vibrational frequencies were measured. References 2 and 5 present data from rotating stall and rotor-blade-vibration investigations conducted on compressors of the same type as used for the investigation reported herein. These investigations concluded that the three-zone stall pattern was the prevailing stall pattern, and that the rotor-blade vibrations were exicted by the second harmonic of the three-zone stall. The data presented herein (fig. 4) also show good correlation between the second harmonic of the three-zone relative stall frequency and the blade-vibration frequency.

Figure 5(a) is a plot of peak vibratory stress against engine speed for the first-stage rotor blades. With the rated exhaust nozzle, the maximum vibratory stress was ±18,300 psi at approximately 60 percent of rated speed. Reducing the exhaust-nozzle area so as to increase the exhaust temperature approximately 250° F increased the peak vibratory stress to ±20,800 psi.

Figure 5(b) is a plot of vibratory stress against engine speed for the second stage. Blade vibration was observed only with the reduced area of the exhaust nozzle. The maximum stress was ±18,450 psi at approximately 68 percent speed. No significant blade vibrations were observed in the third and fourth stages.

Fifth-Stage Bleed

A plot of fifth-stage bleed-flow rate as percent of inlet flow against percent of rated speed with the tenth-stage bleed closed is presented in figure 6. Figure 6(a) shows the data for rated nozzle area, and 6(b) for reduced nozzle area, or an increase in tailpipe gas

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temperature of approximately 250° F. These data indicate the amount of bleed needed to change the stall patterns from a three-zone pattern to a four- or five-zone pattern, the amount needed to eliminate the rotating stall, and the maximum amount of bleed obtainable with this bleed system. Bleed will be discussed principally at the speeds where blade vibration occurred.

With the reduced nozzle area more bleed was required to eliminate the three-zone rotating stall pattern and relieve the rotor-blade vibration than with the rated nozzle. As shown in figures 4 and 5, rotor-blade vibratory stresses excited by three-zone rotating stall were measured in the first and second stages. In the first stage these vibrations occurred at approximately 60 percent of rated speed. With rated and reduced exhaust-nozzle areas 1.5 and 2.8 percent bleed, respectively, were required to change the three-zone stall to a five-zone stall and to eliminate the first-stage peak vibrations. The second-stage peak vibratory stress was observed at 68 percent of rated speed only with reduced exhaust-nozzle area (fig. 5(b)). A bleed-flow rate of less than 1 percent was required to change the three-zone to a five-zone stall and eliminate this vibration.

It would have been desirable to eliminate completely the rotating stall; however, the higher bleed flows required may be detrimental to the engine performance. For this particular compressor, changing the stall pattern from a three-zone to a five-zone pattern satisfactorily reduced the vibration problem. Figure 6(a) indicates the reason for the second-stage vibration's being observed only with the reduced exhaust-nozzle area. At approximately 63 percent of rated speed, with rated exhaust nozzle and no bleed, the compressor stall pattern changed from a three-zone stall pattern and, hence, no resonance occurred.

Tenth-Stage Bleed

Plots of the rotating-stall conditions of the compressor with the tenth-stage bleed-flow rate varied and the fifth-stage bleed closed are presented in figure 7. These data show the bleed-flow rate required to change or eliminate the three-zone rotating-stall pattern at the various percentages of engine rated speed. At the lower speeds high flow rates of bleed were required to change the stall pattern from a three- to a four- or five-zone stall pattern. At 60 percent speed bleed-flow rates of 3.2 and 6.8 percent with rated and reduced exhaust nozzle areas, respectively, were required to change the three-zone stall to a four- or five-zone stall pattern and eliminate the peak vibratory stresses in the first-stage rotor blades. With the tenth-stage bleed less than 1 percent bleed was required to eliminate the peak vibratory stresses in the second-stage blades with reduced nozzle area at 68 percent speed.

Comparison of the data presented in figures 6 and 7 indicates that the fifth-stage bleed was more effective than the tenth-stage bleed; that is, a lower bleed-flow rate was required to eliminate the three-zone stall and the resultant blade vibration.

SUMMARY OF RESULTS

An investigation conducted on a 13-stage axial-flow compressor to determine the effect of fifth- and tenth-stage bleed-flow rate on rotating stall and blade vibration showed that:

1. The three-zone stall pattern prevailed with no bleed flow.

2. The peak vibratory stresses, which were excited by the second harmonic of the three-zone relative stall frequency, occurred in the first and second rotor stages at 60 and 68 percent of rated speed, respectively.

3. With engine operation at rated conditions, a 1.5 or 3.2 percent bleed-flow rate, independently, in the fifth and tenth stages, respectively, was required to eliminate the three-zone stall and the first-stage peak vibratory stresses at 60 percent rated speed.

4. Either fifth- or tenth-stage bleed-flow rates of less than 1 percent were required to eliminate the second-stage peak vibration at approximately 68 percent of rated speed with the reduced exhaust-nozzle area.

5. Higher bleed-flow rates were required to eliminate the vibration when the compressor was operated with a reduced exhaust-nozzle area.

6. The bleed flow required to eliminate completely the rotating stall at the lower engine speeds was possibly large enough to have a detrimental effect on engine performance. Since the three-zone stall pattern was the only pattern in resonance with the first- and second-stage rotor blades, eliminating the three-zone stall was sufficient to eliminate the blade vibrations.

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National Advisory Committee for Aeronautics
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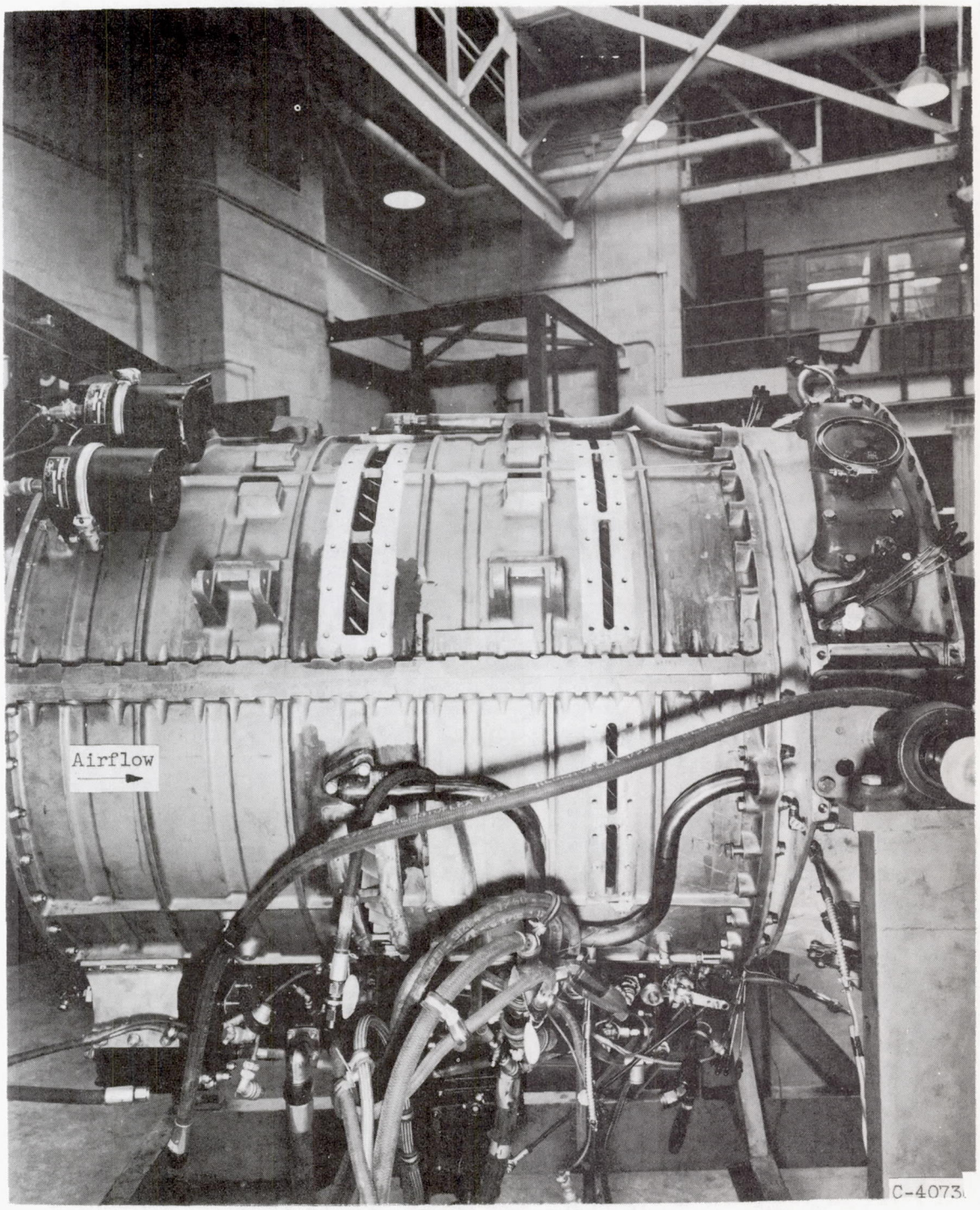
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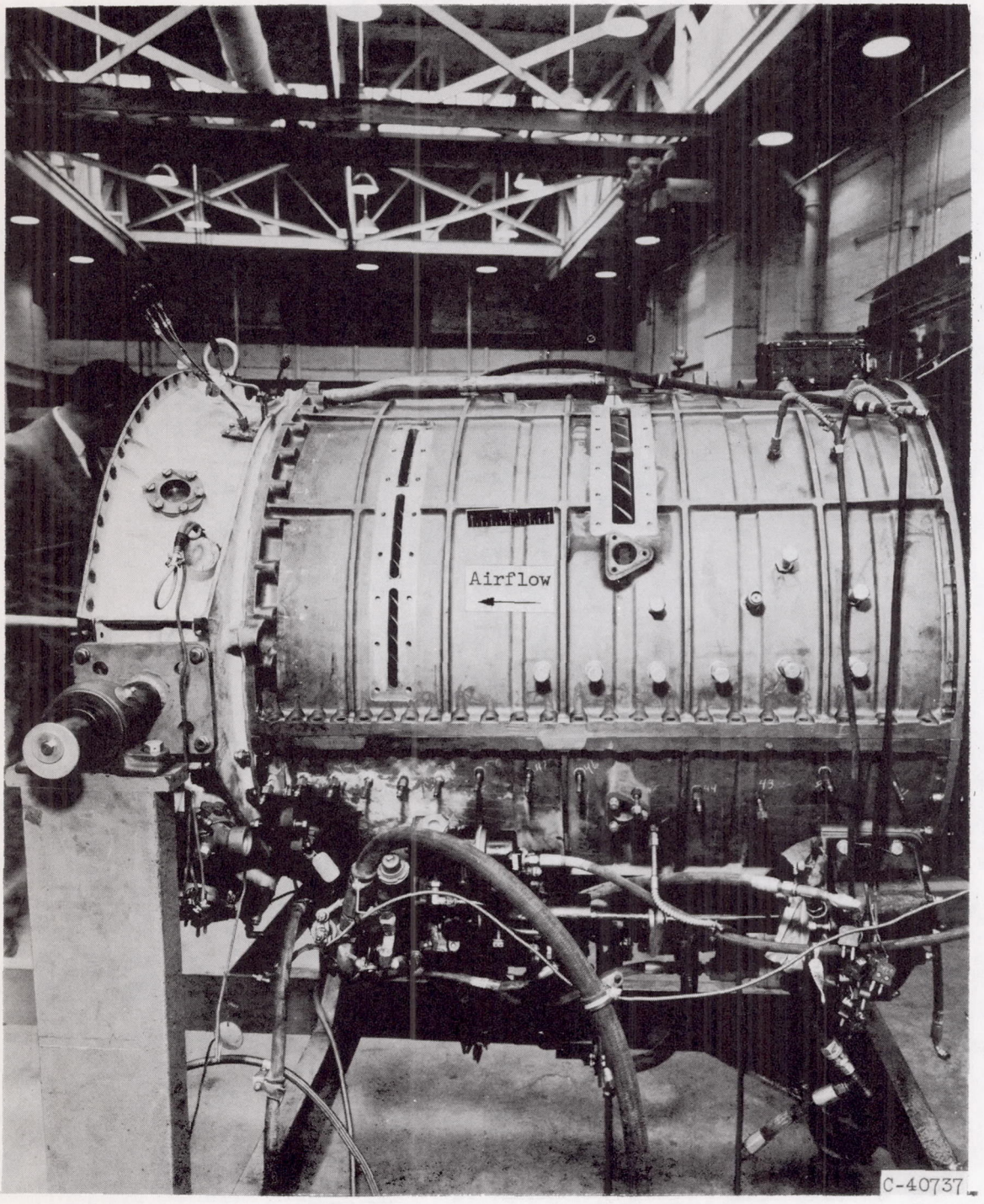
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(a) Right side of compressor case.

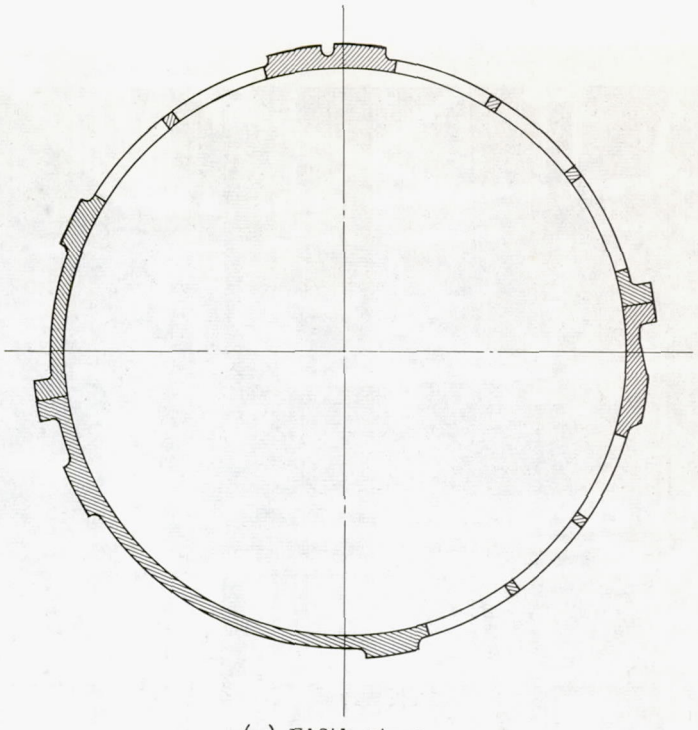
Figure 1. - Fifth- and tenth-stage interstage bleed passages in case.



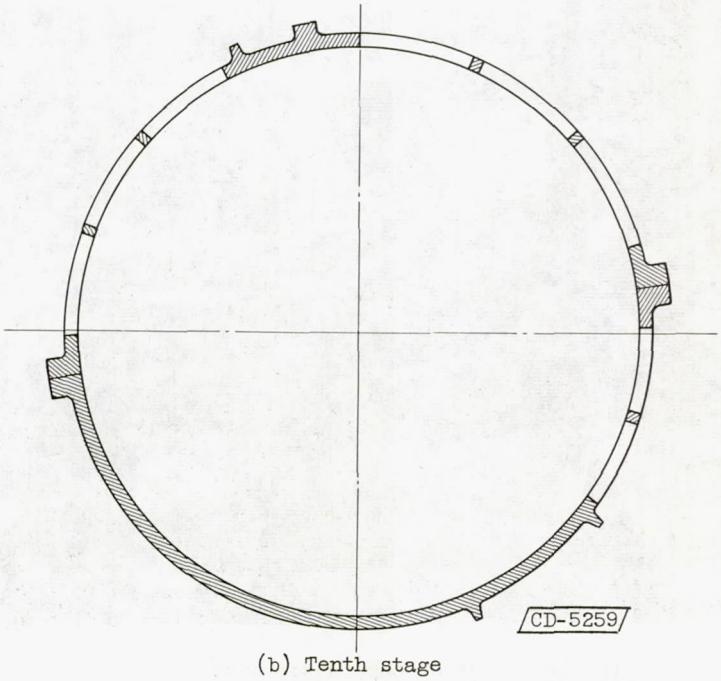
(b) Left side of compressor case.

Figure 1. - Concluded. Fifth- and tenth-stage interstage bleed passages in case.

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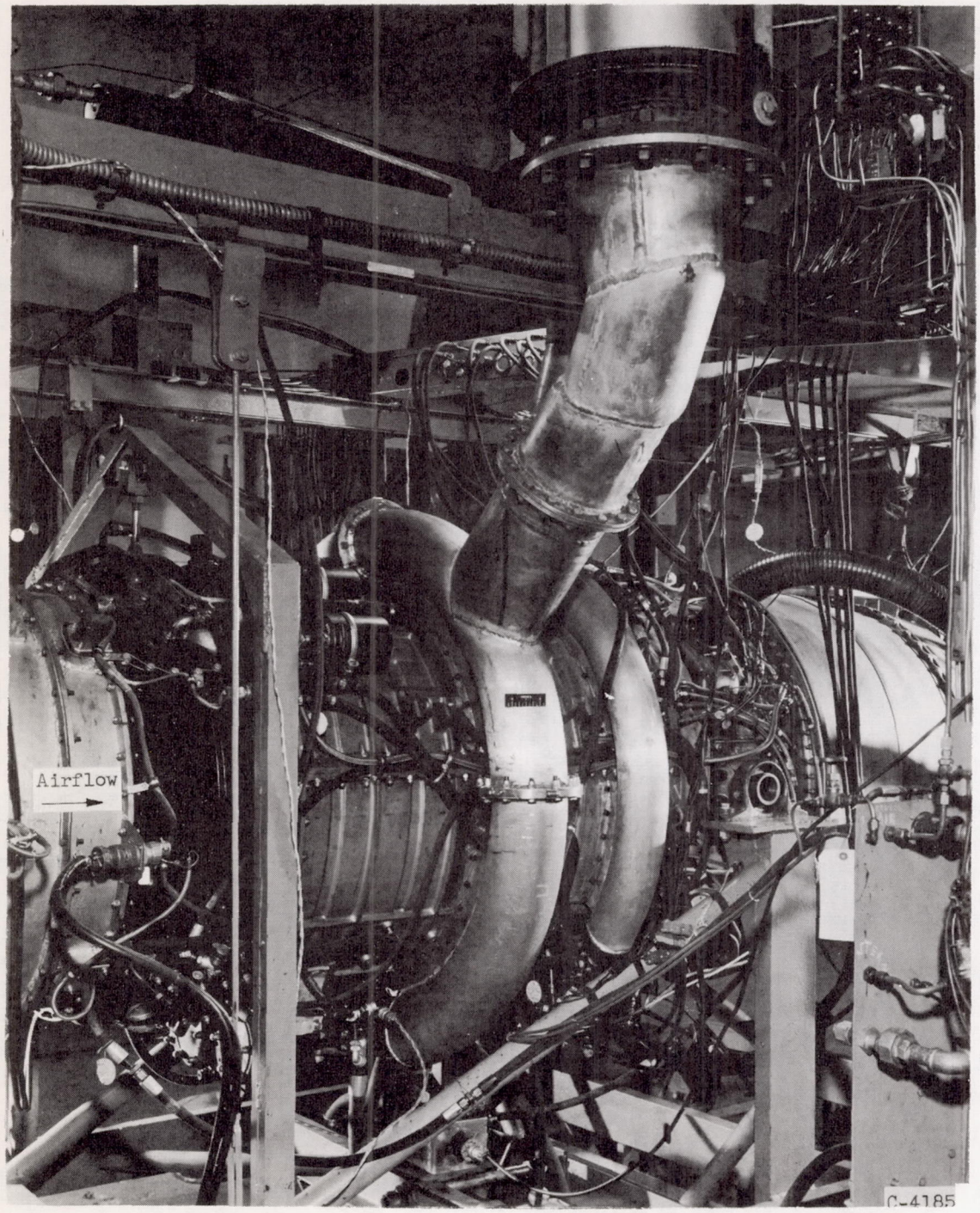
(a) Fifth stage.



(b) Tenth stage

Figure 2. - Cross sections of compressor case at fifth- and tenth-stage bleed slots.

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Right side of engine.

Figure 3. - Fifth- and tenth-stage interstage bleed piping system.

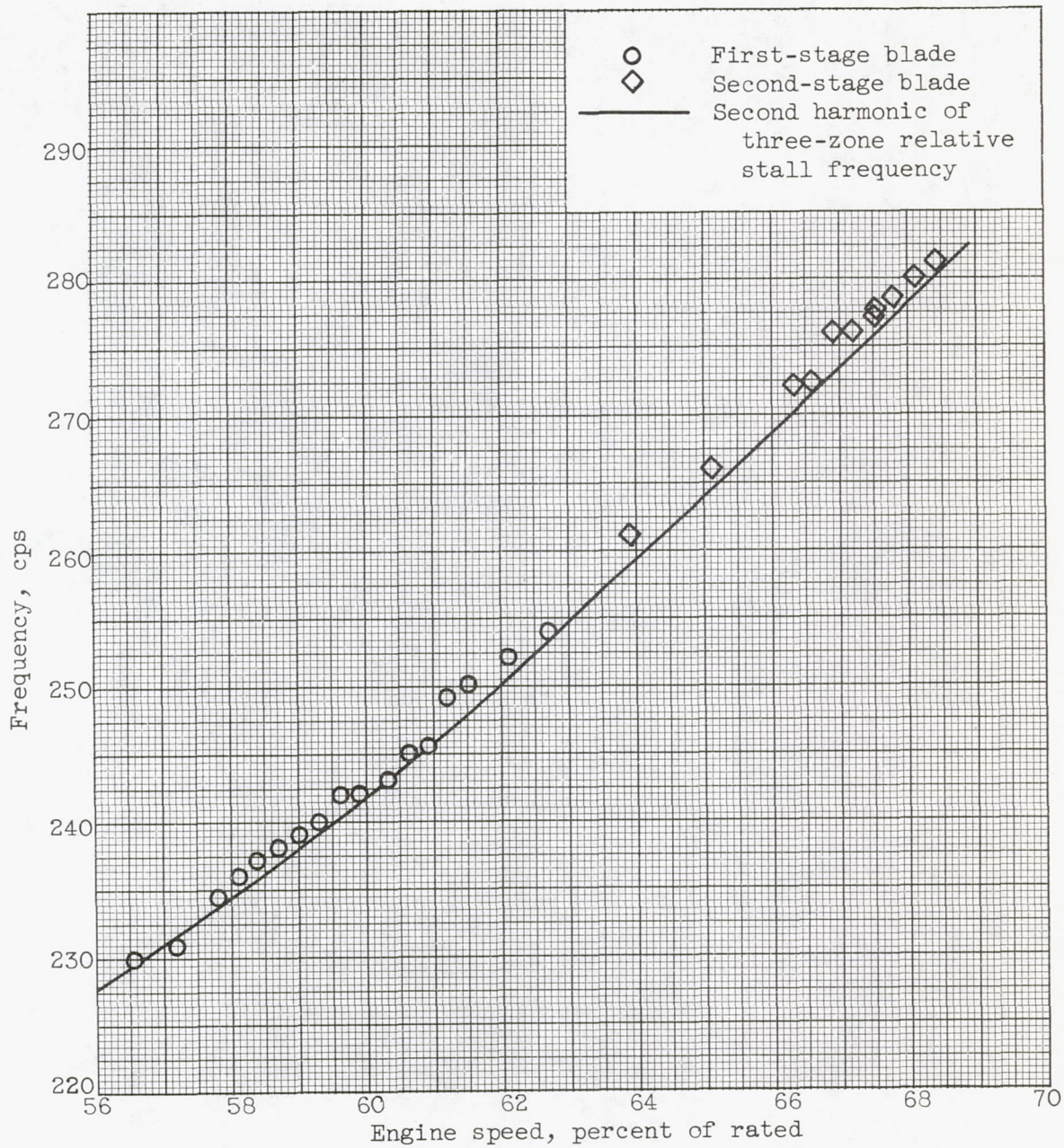
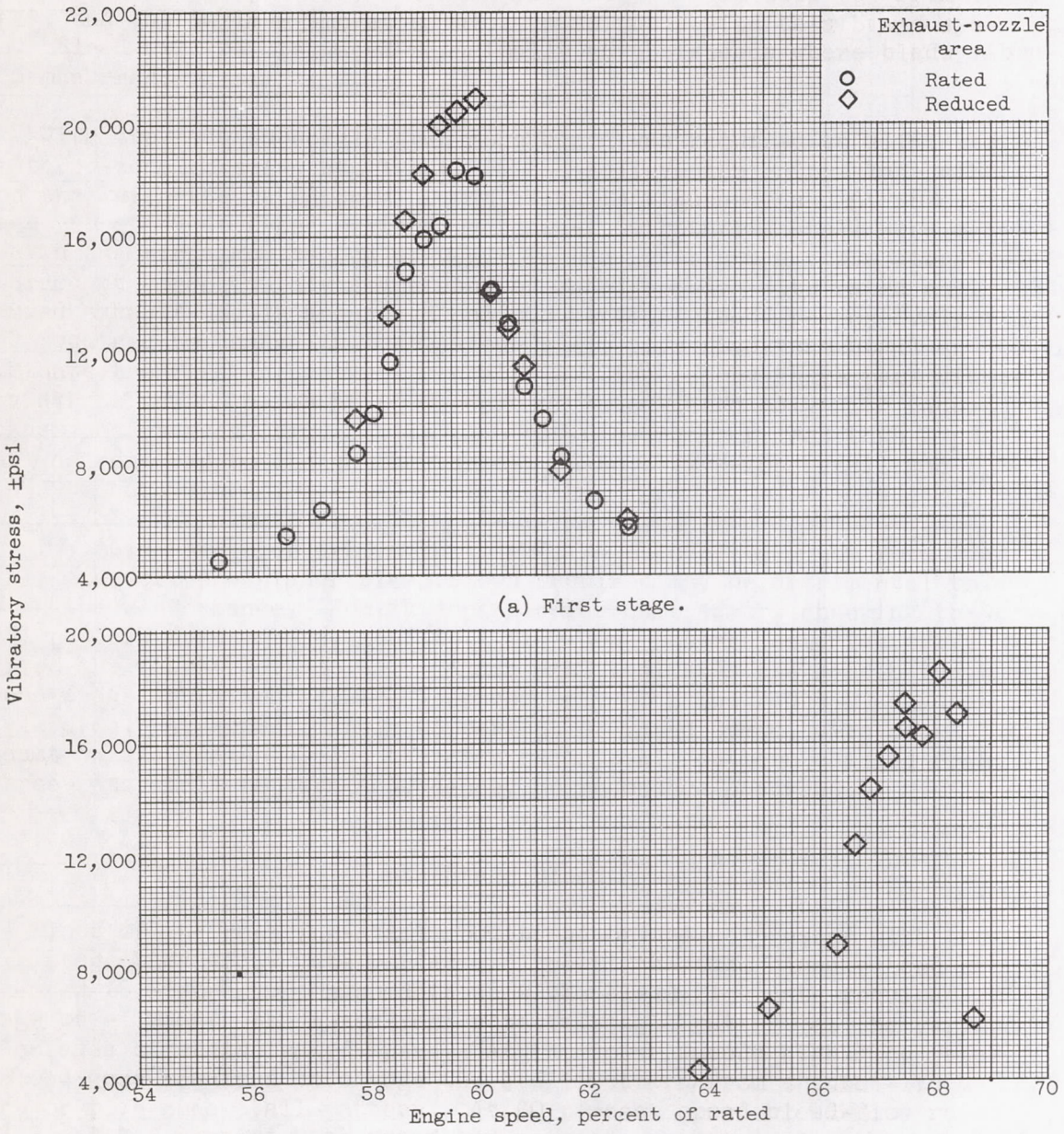


Figure 4. - Correlation between rotor-blade and three-zone rotating-stall frequency.

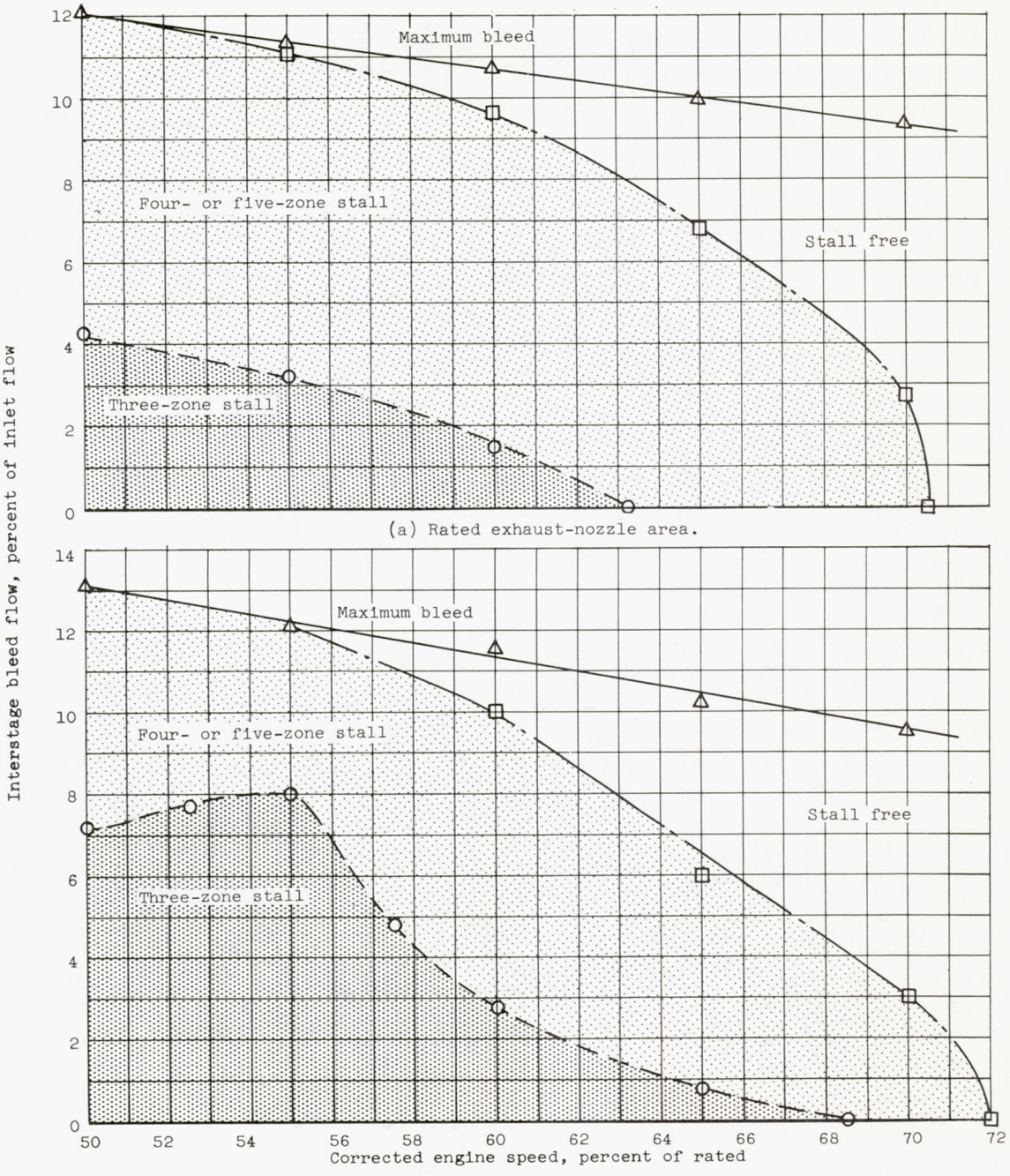
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(a) First stage.

(b) Second stage.

Figure 5. - Vibratory bending stresses of rotor blades. Bleeds closed.

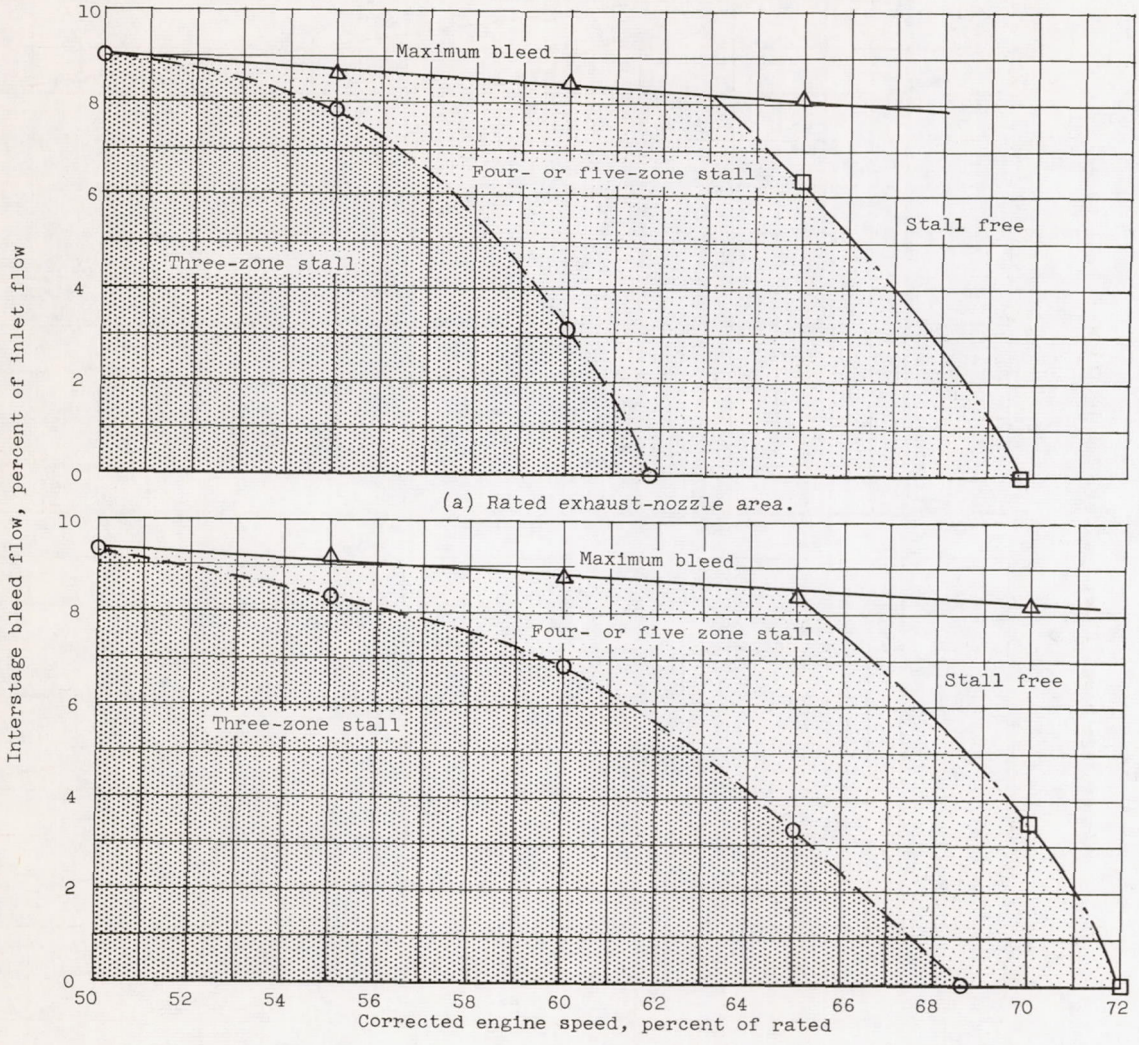


(a) Rated exhaust-nozzle area.

(b) Reduced exhaust-nozzle area.

Figure 6. - Effect of fifth-stage bleed on rotating stall. Tenth-stage bleed closed.

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(a) Rated exhaust-nozzle area.

(b) Reduced exhaust-nozzle area.

Figure 7. - Effect of tenth-stage bleed on rotating stall. Fifth-stage bleed closed.